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In situ Measurements of Tide Gauge Response and Corrections of Tsunami Waveforms from the Niigataken Chuetsu-oki Earthquake in 2007

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Abstract—Linear and nonlinear responses of ten well-type tide gauge stations on the Japan Sea coast of central Japan were estimated by *in situ* measurements. We poured water into the well or drained water from the well by using a pump to make an artificial water level difference between the outer sea and the well, then measured the recovery of water level in the well. At three tide gauge stations, Awashima, Iwafune, and Himekawa, the sea-level change of the outer sea is transmitted to the tide well instantaneously. However, at seven tide gauge stations, Nezugaseki, Ryotsu, Ogi, Teradomari, Banjin, Kujiranami, and Naoetsu, the sea-level change of the outer sea is not always transmitted to the tide well instantaneously. At these stations, the recorded tsunami waveforms are not assured to follow the actual tsunami waveforms. Tsunami waveforms from the Niigataken Chuetsu-oki Earthquake in 2007 recorded at these stations were corrected by using the measured tide gauge responses. The corrected amplitudes of the first and second waves were larger than the uncorrected ones, and the corrected peaks are a few minutes earlier than the uncorrected ones at Banjin, Kujiranami, and Ogi. At Banjin, the correction was significant; the corrected amplitudes of the first and second upward motion are +103 cm and +114 cm, respectively, while the uncorrected amplitudes were +96 cm and +88 cm. At other tide gauge stations, the differences between the uncorrected and corrected tsunami waveforms were insignificant.

Key words: *In situ* measurement, Tide gauge response, Corrected tsunami waveform, The Niigataken Chuetsu-oki Earthquake in 2007.

1. *Introduction*

A large earthquake occurred off the coast of Niigata Prefecture, Japan, at 10:13 a.m. (JST) July 16th, 2007. The Japan Meteorological Agency (JMA) estimated its magnitude to be 6.8 and named it the Niigataken Chuetsu-oki Earthquake in 2007. About 1,300

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houses were completely destroyed around the source area and 15 people were killed. The earthquake was accompanied by a tsunami with maximum amplitude of about 1 m recorded at the tide gauge station at Banjin, Kashiwazaki City, near the source region.

Three types of tide gauge systems are generally used in Japan: a well type, which records vertical motion of a float in a tide well connected with one or more intake pipes to the outer sea; a pressure type, which records hydrostatic pressure; and an acoustic type, which records distance between the sea surface and the sensor by acoustic waves. The tide gauge system of Banjin is of the well type. For this type, because of the narrow and/or long intake pipe, waves such as the astronomical tide with periods longer than several hours are faithfully recorded, but short-period waves with periods of less than several seconds such as wind wave or swell are mostly cut off. The response to a tsunami, having energy in the intermediate-period band of a few to a few ten minute periods is not well known. The intake pipes of tide gauge stations on the Japan Sea coast are usually narrow because of the severe sea conditions in winter. Therefore, in order to estimate the actual, or true, tsunami waveforms from the tide gauge records, it is necessary to correct them using the measured tide gauge response.

There have been several studies on tide gauge response. Shipley (1963) studied a tide gauge system where the tide well is connected to the outer sea by an intake pipe. Cross (1967) studied a tide gauge system in which the tide well is directly connected to the outer sea at an orifice without an intake pipe. They proposed a nonlinear response such that the temporal change of the water level in the well is proportional to the square root of the level difference between the outer sea and the well by using Bernoulli's theorem.

Noye (1974a) examined a well system with long intake pipe, and proposed a linear response such that the temporal change of the water level in the well is proportional to the level difference between the outer sea and the well, assuming the flow in the intake pipe is a steady Poiseuille flow. If the length of the intake pipe is not too long and/or the diameter is not too small, the linear and nonlinear responses should be combined for tide gauge corrections (Noye, 1974b).

Loomis (1983) calculated a nonlinear response to pseudo-tsunami by using running white noise, and showed that the larger the amplitude or the broader the spectrum of the tsunami, the greater the difference between the original and corrected waveforms.

Okada (1985) carried out *in situ* measurements of the tide gauge response at Maizuru, Japan, and concluded that the observation was in better agreement with a nonlinear response than with a linear response. He also corrected the tsunami waveform of the 1983 Nihonkai-chubu (Japan Sea) earthquake (M_w 7.9) tsunami at Fukaura, Japan, using the nonlinear response.

Satake *et al.* (1988) conducted *in situ* measurements of the response at 40 tide gauge stations on the coasts of northern Japan, and corrected tsunami waveforms of the 1983 earthquake using nonlinear responses. For this tsunami, the amplitudes recorded at some tide gauge stations were considerably smaller than the visually observed inundation heights (Kinoshita *et al.*, 1984). The maximum tsunami heights corrected by Satake *et al.* (1988) agreed well with the visually observed ones. Satake *et al.* (1988) also estimated the theoretical hydraulic coefficients of the tide gauge response, but they concluded that the theoretical coefficients poorly coincided with those obtained by *in situ* measurements.

These previous studies mainly considered the effects of nonlinear response. However, since the lengths and diameters of the intake pipes of tide wells in Japan vary, we cannot exclude the possibility that some of the tide gauge response may include a linear component as proposed by Noye (1974b). Moreover, about 20 years have passed since the previous studies, and circumstance of the intake pipes might be different. For example, the tide gauge stations at Naoetsu and Ogi moved after the measurements by Satake *et al.* (1988).

In the present study, we carry out *in situ* measurements at ten tide gauge stations. They are located at Nezugaseki (38°33'48"N, 139°32'45"E), Ogi (37°48'53"N, 138°16'52"E), and Kujiranami (37°21'24"N, 138°30'30"E), operated by the Geographical Survey Institute (GSI), at Awashima (38°28'04"N, 139°15'18"E) operated by Japan Coast Guard (JCG), at Iwafune (38°11'29"N, 139°25'51"E), Ryotsu (38°05'00"N, 138°26'10"E), Teradomari (37°38'36"N, 138°45'58"E), Banjin (37°21'55"N, 138°31'51"E), Naoetsu (37°11'06"N, 138°15'12"E), and Himekawa (37°02'22"N, 137°50'11"E), operated by Niigata Prefecture (Fig. 1). We estimate the tide gauge

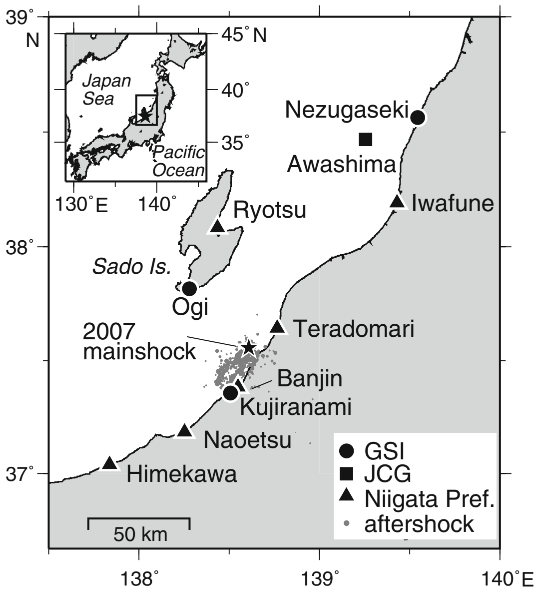

Figure 1
Location of the tide gauge stations whose responses were estimated by *in situ* measurements in the present study. The circles, square, and triangles indicate the tide gauge stations operated by Geographical Survey of Japan (GSI), Japan Coast Guard (JCG), and Niigata Prefecture, respectively. The aftershocks (gray dots) located by JMA within 1 day after the main shock (star) are also shown.

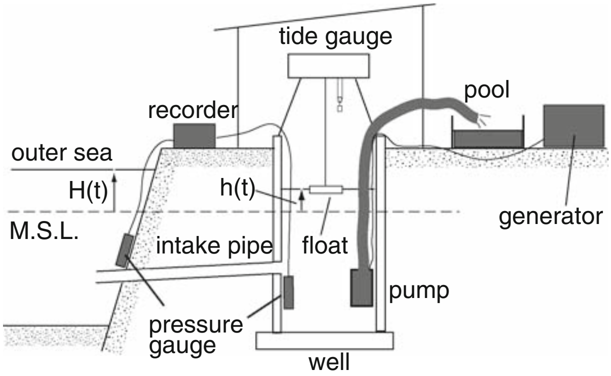

Figure 2
Schematic diagram for a typical tide gauge well structure in Japan. The pressure gauges, recorder, pump, pool, and generator (colored gray) are set up temporarily for *in situ* measurements. $H(t)$ and $h(t)$ denote the water levels of the outer sea and the well, respectively, above the mean sea level (M.S.L.).

responses with linear and nonlinear effects combined. Using the measured responses, we also correct the tsunami waveforms of the Niigataken Chuetsu-oki Earthquake in 2007.

2. *Theory and Method for Tide Gauge Response and Tsunami Waveform Correction*

2.1. *Linear and Nonlinear Responses of Tide Well*

In a typical tide well in Japan (Fig. 2), the well is connected to the outer sea with a long and narrow intake pipe. It usually records the long-period waves like astronomical tides and the vertical deformation due to long-term crustal motion, and short-period waves like wind wave or swell are cut off due to the existence of the narrow intake pipe. However, a tsunami having intermediate periods of a few to a few tens of minutes may not be faithfully recorded, because the change in the outer sea level caused by a tsunami is sometimes so large and rapid that the tide gauge system cannot follow it instantaneously.

When the water level in the well becomes different from the outer sea level, the nonlinear response based on Bernoulli's theorem is expressed as

$$\frac{dh(t)}{dt} = W\mathrm{sgn}\{H(t) - h(t)\}\sqrt{2g|H(t) - h(t)|}, \tag{1}$$

where t, $H(t)$, $h(t)$, and g denote time, the outer sea and the well levels, and gravitational acceleration, respectively (Fig. 2). The operation $\mathrm{sgn}(x)$ indicates the sign function. It takes the value $+1$ when there is inflow, and it takes the value -1 when there is outflow. The value, W, is a non-dimensional coefficient of the nonlinear response (nonlinear coefficient) to be estimated by *in situ* measurements (e.g. SATAKE *et al.*, 1988).

When the intake pipe is long and/or narrow, the flow in the intake pipe becomes like a steady Poiseuille flow (e.g., NOYE, 1974b). In this case, the response becomes linear, and is described as

$$\frac{dh(t)}{dt} = \frac{1}{G}\{H(t) - h(t)\}, \tag{2}$$

where G is the coefficient of the linear response with unit of time (linear coefficient), also to be estimated by *in situ* measurements.

When the length of the intake pipe is not too long and/or the diameter is not too small, the response of the well level is regarded as a combination of linear and nonlinear responses. Then, the response can be described as

$$\frac{dh(t)}{dt} = gW^2 \mathrm{sgn}\{H(t) - h(t)\}\left\{-G + \sqrt{G^2 + \frac{2|H(t) - h(t)|}{gW^2}}\right\}, \tag{3}$$

(e.g., NOYE, 1974b). Note that equation (3) becomes a nonlinear equation (1), when the linear response is negligible, that is, $G = 0$. Because of the long and/or narrow intake pipes, we consider equation (3).

2.2. *In situ Measurement of Tide Well Response*

The nonlinear coefficient W can be calculated by theoretical hydraulic considerations. However, SATAKE *et al.* (1988) pointed out that the theoretical coefficients can be as much as ten times larger than those obtained by *in situ* measurements. The large discrepancy is attributed to the inaccurate estimation of the friction in the intake pipe, because theoretical considerations do not account for the effect of marine organisms and sediment on it. Therefore, the actual coefficients should be estimated by *in situ* measurements.

In the *in situ* measurement, we first prepare two pressure gauges, a pump, pool, and generator (the gray symbols shown in Fig. 2). One pressure gauge is set up in the well and the other is set up near the mouth of the intake pipe in the outer sea. The pump is set up in the well, and the generator, which supplies electric power for the pump, and pool are set up on the ground near the well.

Next, water in the well is drained up to the pool by the pump until the water level in the well becomes significantly lower than that of the outer sea. Then we stop the pump, and measure the naturally recovering water level by using the pressure gauge, until the water level in the well becomes the same as that of the outer sea. This measurement is for the response of inflow from the outer sea to the well (inflow experiment).

We also carry out *in situ* measurements for outflow. In this case, we set up the pump in the pool filled with sea water. We then pour the water from the pool to the well, increasing the water level in the well with respect to the outer sea (outflow experiment). The pool is needed for the outflow experiments, but at Ryotsu and Himekawa, we directly poured water from the outer sea, because the tide well is located so close to the outer sea.

These inflow and outflow measurements are similar to Satake *et al.* (1988), however, they observed the well-water levels manually with a sampling interval of about 3 sec, because portable pressure gauges were not available. Moreover, they did not observe the outer sea level, and regarded it as the same as that in the well after the recovery. For our case, we measured the water levels both of the outer sea and the well by pressure gauges whose sampling interval is 1 sec for the tide well and 2 sec for the outer sea. We also manually observed the water level in the well with a sampling interval of about 3 sec, and recorded it by video camera.

2.3. *Estimation of Linear and Nonlinear Coefficients G and W*

In order to obtain the linear and nonlinear coefficients G and W in equation (3), we adopt a grid search method. First, we assume a W-G plane with a search area of $0.00001 \leqq W \leqq 0.01$ and $0 \leqq G \leqq 100$ sec, represented by $1{,}000 \times 1{,}000$ grid points with intervals of $\Delta W = 0.00001$ and $\Delta G = 0.1$ sec (Fig. 3a). Next, the recovering well levels after stopping the pump are calculated from equation (3) by the Runge-Kutta method, using

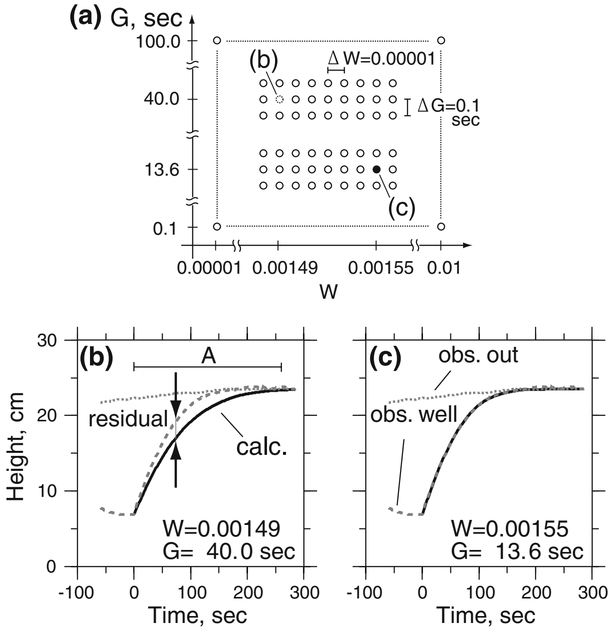

Figure 3
Schematic illustration of the grid-search method (see text). (a) Schematic W-G plane used for the grid search method. (b) Observed recovering well level (gray dashed line) for inflow and calculated one (solid line) by the Runge-Kutta method using the trial values for the coefficients $W = 0.00149$ and $G = 40.0$ sec at Banjin. The outer sea level is also shown (gray dotted line). The belt A indicates the time range in which the TASR is calculated. (c) Same as (b), but using the estimated linear and nonlinear coefficients which give the minimum TASR.

the coefficients at each grid point (W, G) as trial values (Fig. 3b). The temporally averaged-squared residual (TASR) between the observed and calculated levels is also calculated for each grid point, from the time the pump was stopped until the well water level reaches the same level of the outer sea. Then, the values of G and W which take the minimum TASR are regarded as the linear and nonlinear coefficients (Fig. 3c). We estimate the coefficients for inflow and outflow separately.

Because the water levels of the outer sea and the well are measured separately using two portable pressure sensors, the average level of the well after the recovery is set to be the same as that of the outer sea.

2.4. *Corrections of Tide Gauge Records*

The corrections of tide gauge records using the combined linear and nonlinear responses can be expressed as follows (NOYE, 1974b),

$$H(t) = h(t) + G\frac{dh(t)}{dt} + \frac{1}{2gW^2}\left(\frac{dh(t)}{dt}\right)^2 \mathrm{sgn}\left(\frac{dh(t)}{dt}\right). \tag{4}$$

Note that positive dh/dt means inflow and negative means outflow. Therefore, the coefficients obtained by the inflow and outflow experiments should be used for the positive and negative dh/dt, respectively.

3. *Results of in situ Measurements*

3.1. *Linear and Nonlinear Coefficients*

We carry out the inflow and outflow experiments at ten well-type tide gauge stations, and estimate the linear and nonlinear coefficients G and W by the grid search method. The results are shown in Figure 4, and Tables 1 and 2. At Nezugaseki, Ryotsu, Ogi, Teradomari, Banjin, Kujiranami, and Naoetsu, significant differences of the water levels between the outer sea and well could be produced using the pump, and the coefficients are obtained by the grid search method. A smallest value for the nonlinear coefficient W is estimated to be 0.00061 for the inflow and 0.00055 for the outflow at Kujiranami, while the largest value is estimated to be 0.00684 for the inflow at Teradomari and 0.00321 for the outflow at Naoetsu. Equations (3) and (4) indicate that the small nonlinear coefficient yields long recovery time and large water-level difference. The recovery times at Kujiranami, where the nonlinear coefficients take small values, are in fact long, while those at Naoetsu and Teradomari, where the nonlinear coefficients take large values, are short. At Nezugaseki, because of the severe sea condition at the time of measurement, strong short-period wave energy was transmitted to the tide well. Therefore, the TASR at Nezugaseki is large and the estimation of the linear and nonlinear coefficients might include some errors. Moreover, comparison of the recovering well levels between inflow

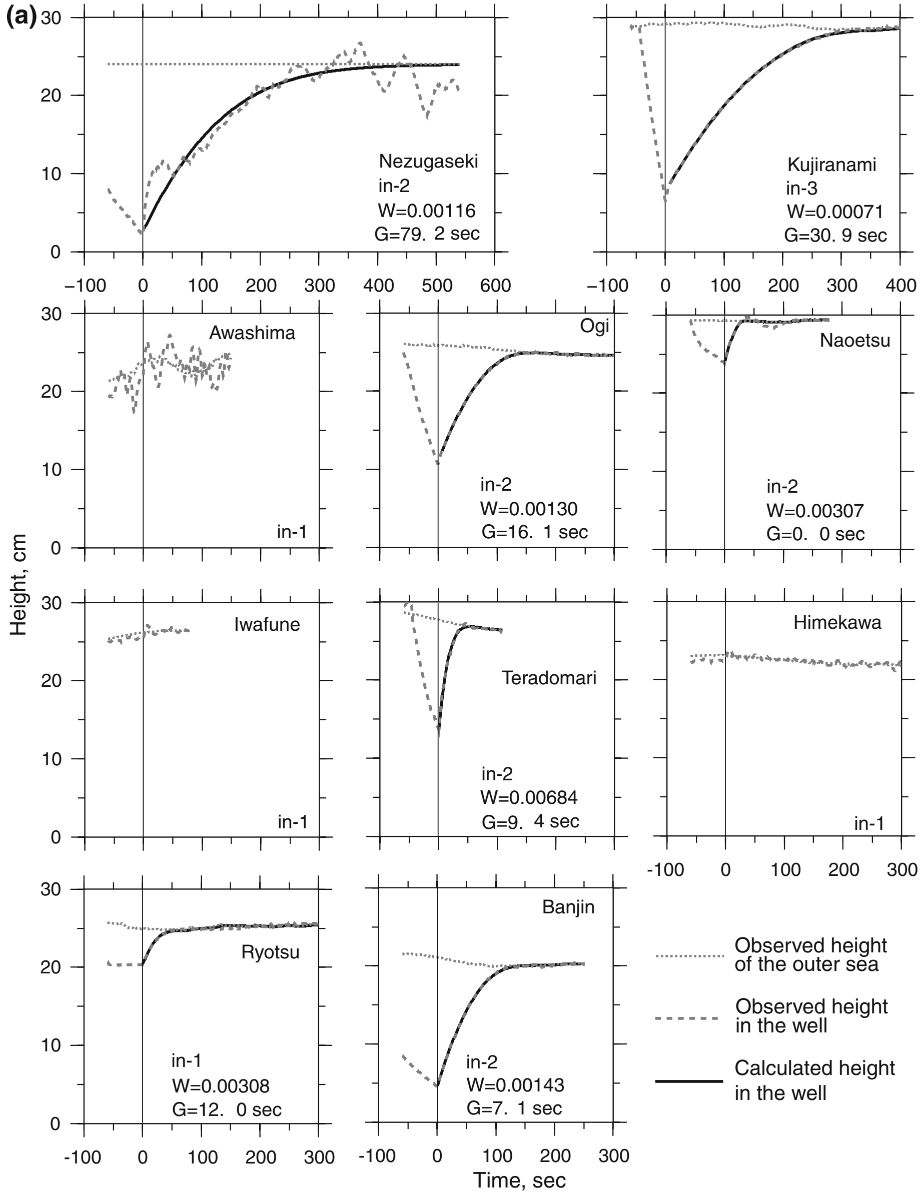

Figure 4

Results of the *in situ* measurements for ten tide gauge stations. (a) The observed recovering well levels (gray dashed lines) for inflow, outer sea levels (gray dotted lines), and the calculated recovering well levels (solid lines) using the estimated linear and nonlinear coefficients G and W (see Table 1). The code name indicates the experiment; e.g., in-2 is the second inflow experiment. Because the significant differences of the water levels between the outer sea and the well could not be made at Awashima, Iwafune, and Himekawa, the linear and nonlinear coefficients are not estimated. At Nezugaseki, because the pressure gauge in the outer sea was out of order, the outer sea level is assumed to be as indicated. (b) Same as (a), but for the outflow experiments.

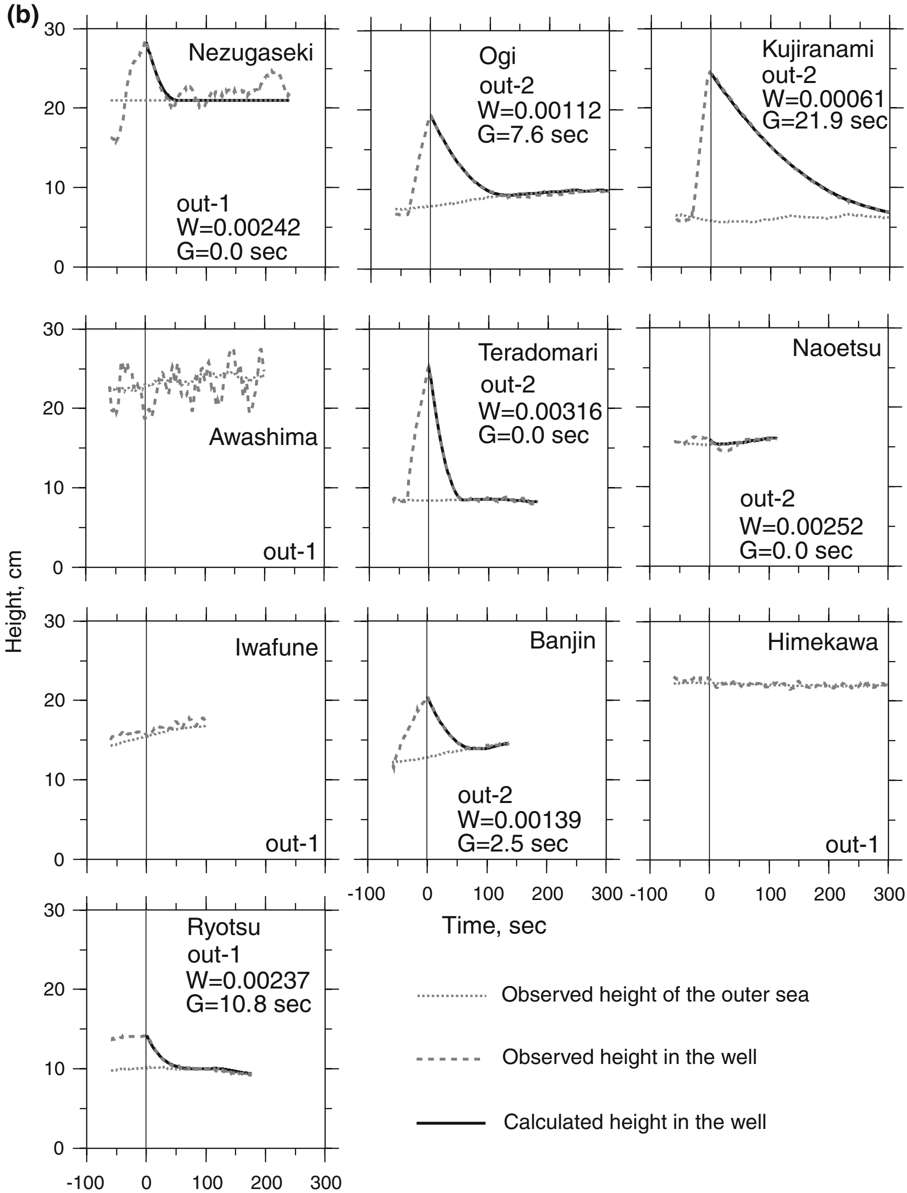

Figure 4
contd.

Table 1

The linear and nonlinear coefficients estimated from the in situ inflow experiments

Station	No.	W	G (sec)	TASR (m^2)	A	Ww	$TASR_w$	Obs. Date
Nezugaseki	1	0.00070	100.0	8.14E-04		0.00743	1.33E-03	22 Nov., 07
	2	0.00116	79.2	2.89E-04	*	0.00705	3.00E-03	
Awashima								23 Nov., 07
Iwafune								13 Sep., 07
Ryotsu	1	0.00308	12.0	5.95E-07	*	0.00183	2.29E-06	19 Sep., 07
	3	0.00303	11.7	7.85E-07		0.00180	2.49E-06	
Ogi	1	0.00126	10.8	5.68E-07		0.00113	1.81E-06	19 Sep., 07
	2	0.00130	16.1	2.79E-07	*	0.00109	2.65E-06	
Teradomari	2	0.00684	9.4	8.33E-06	*	0.00404	2.16E-05	13 Sep., 07
	3	0.00506	6.4	1.13E-05		0.00389	1.74E-05	
Banjin	1	0.00155	13.6	7.25E-07		0.00130	4.41E-06	11 Sep., 07
	2	0.00143	7.1	5.00E-07	*	0.00132	1.23E-06	
	3	0.00142	4.7	7.68E-07		0.00135	1.23E-06	
Kujiranami	1	0.00079	34.2	2.62E-06		0.00065	8.92E-06	11 Sep., 07
	2	0.00061	35.1	2.34E-06		0.00051	5.30E-06	
	3	0.00071	30.9	8.34E-07	*	0.00061	5.10E-06	
Naoetsu	1	0.00299	0.0	5.41E-07		0.00299	5.41E-07	12 Sep., 07
	2	0.00307	0.0	5.40E-07	*	0.00307	5.40E-07	
	3	0.00324	0.0	6.15E-07		0.00324	6.15E-07	
	4	0.00296	0.0	8.00E-07		0.00296	8.00E-07	
Himekawa								20 Sep., 07

The values of G and W with symbol * in column A are the best linear and nonlinear coefficients used for the corrections of tsunami waveforms. TASR is the temporally averaged-squared residual (in m^2). The subscript "w" denotes the values of the nonlinear response, which is estimated by the grid search method, assuming that the linear coefficient $G = 0$.

and outflow at Nezugaseki shows that the artificial water-level difference for inflow is much larger than and the recovery for inflow is slower than those for outflow. This discrepancy is attributed to an insufficient setting for the outflow experiment at Nezugaseki where the recovery time is considerably long. The amount of water pumped from the pool was not sufficient to raise the well water level enough to conduct the outflow experiment. Therefore, the coefficients for outflow at Nezugaseki may be unreliable.

At Naoetsu and Teradomari, the linear coefficient G is estimated as zero. This means that the tide gauge response for inflow and/or outflow is completely nonlinear at these sites.

At Awashima, Iwafune, and Himekawa, no significant difference of the water level between the outer sea and well could be produced using the pump both for the inflow and outflow experiments. Such an insignificant difference suggests that the outer sea-level change transmits to the well almost instantaneously, and the tsunami waveforms recorded in the well can be regarded as the actual or true tsunami waveforms of the outer sea. Therefore, in the present study, no corrections are made for the recorded tsunami waveforms at the above three tide gauge stations. The observed oscillation in inflow experiment at Awashima can be explained by the characteristic oscillation of the tide gauge system consisting of intake pipe and tide well.

Table 2

The linear and nonlinear coefficients estimated from the in situ outflow experiments

Station	No.	W	G (sec)	TASR (m^2)	A	Ww	$TASR_w$	Obs. Date
Nezugaseki	1	0.00242	0.0	9.59E-07		0.00242	9.59E-07	22 Nov., 07
Awashima								23 Nov., 07
Iwafune								13 Sep., 07
Ryotsu	1	0.00237	10.8	8.21E-07	*	0.00160	1.75E-06	19 Sep., 07
	2	0.00209	6.4	1.06E-06		0.00168	1.37E-06	
Ogi	1	0.00132	22.7	6.83E-07		0.00100	3.80E-06	19 Sep., 07
	2	0.00112	7.6	4.19E-07	*	0.00103	7.76E-07	
Teradomari	1	0.00309	0.0	5.81E-06		0.00309	5.81E-06	13 Sep., 07
	2	0.00316	0.0	5.68E-07	*	0.00316	5.68E-07	
Banjin	1	0.00143	3.2	8.13E-07		0.00135	8.95E-07	11 Sep., 07
	2	0.00139	2.5	3.26E-07	*	0.00134	3.67E-07	
Kujiranami	1	0.00055	1.8	1.33E-06		0.00055	1.61E-06	11 Sep., 07
	2	0.00061	21.9	8.61E-07	*	0.00055	2.70E-06	
Naoetsu	1	0.00273	0.0	5.46E-07		0.00273	5.46E-07	12 Sep., 07
	2	0.00252	0.0	2.86E-07	*	0.00252	2.86E-07	
	3	0.00298	0.0	1.58E-06		0.00298	1.58E-06	
	4	0.00244	0.0	1.09E-06		0.00244	1.09E-06	
	5	0.00321	0.0	2.53E-06		0.00321	2.53E-06	
Himekawa								20 Sep., 07

The legend is the same as Table 1.

During the inflow experiments at Iwafune and Himekawa, we could not produce significant water level differences, and the flow in the intake pipe was steady. We measured the steady flow rate of 2.6 liter/sec at Iwafune, and 3.5 liter/sec at Himekawa by using a scaling bucket.

At Iwafune, the intake pipe was cleaned in February 2007, which is 7 months before the experiment or 5 months before the tsunami. Hence the tide response is good at this station. At Nezugaseki, it was also cleaned in October 2007, which is 1 month before the experiment but 4 months after the tsunami. Therefore, the obtained linear and nonlinear coefficients at Nezugaseki may not be the same as those at the time of the tsunami from the Niigataken Chuetsu-oki Earthquake in 2007.

During the inflow experiments at Kujiranami and Ogi, the backward (rebound) flow from the pump into the well was observed just after we stopped the pump. Hence, the observed well level recovered more quickly than the well level governed by equation (3) does (Fig. 5a). In these cases, as the initial condition for the Runge-Kutta method, we use the observed well level at the time when the backward flow is just completed rather than when we stopped the pump (Fig. 5b).

At Teradomari and Naoetsu, inertial oscillations were observed after the well level recovered to the outer sea level (Fig. 5c). This phenomenon cannot be explained by equation (3), and therefore, the mean level of the oscillation is considered as the outer sea level just after the recovery (region A in Fig. 5c).

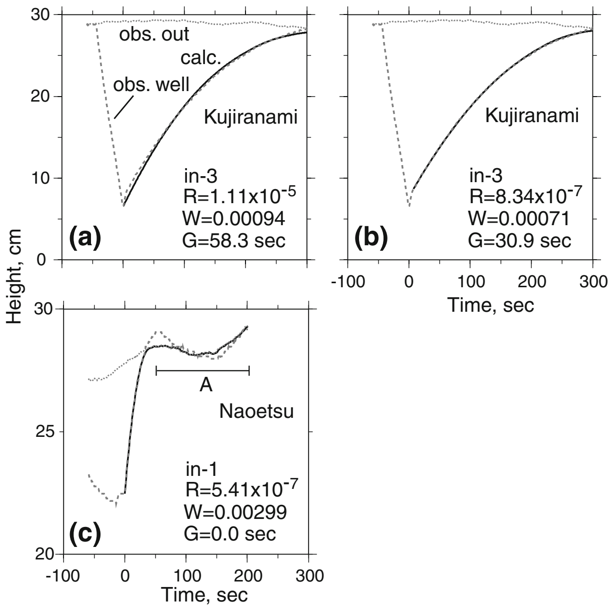

Figure 5
(a) Recovering well level (the black solid line) for the third inflow experiment (in-3) at Kujiranami calculated by the Runge-Kutta method with the initial height at t = 0 (just after we stopped the pump). The gray dotted and dashed lines are the observed outer sea and the well levels, respectively. R, W, and G denote TASR and nonlinear and linear coefficients, respectively. Because of the influence of the backward flow, the calculated recovering well level does not completely coincide with the observed one even if the linear and nonlinear coefficients estimated by the grid-search method are used. (b) Recovering well level for the same case as (a) calculated with the initial height at t = 7 sec (when the backward flow from the pump ended). In this case, the calculated recovering well level coincides with the observed one. (c) Recovering sea level for the first inflow experiment (in-1) at Naoetsu calculated by referencing the outer sea level to the mean well level in range A.

3.2. Best Linear and Nonlinear Coefficients

Several inflow and outflow experiments were carried out at each tide gauge station, and the linear and nonlinear coefficients are estimated by a grid search method for each experiment. In the present study, among the estimated linear and nonlinear coefficients for each experiment, those with the minimum TASR are regarded as the best pairs for inflow or outflow at the tide gauge station. For example, at Banjin, we made three inflow experiments and two outflow experiments, and the linear and nonlinear coefficients of the second inflow and outflow experiments yield the minimum TASR (Tables 1 and 2). Hence the pairs $W = 0.00143$ and $G = 7.1$ sec for inflow and $W = 0.00139$ and $G = 2.5$ sec for outflow are regarded as the best linear and nonlinear coefficients at Banjin.

To confirm the reproducibility of experiments, we check the distributions of TASR for the inflow and outflow experiments at each tide gauge station (Fig. 6). The figure shows that the distribution of TASR is similar for repeated inflow or outflow experiments at each tide gauge station, and indicates that repeated experiments yield similar results.

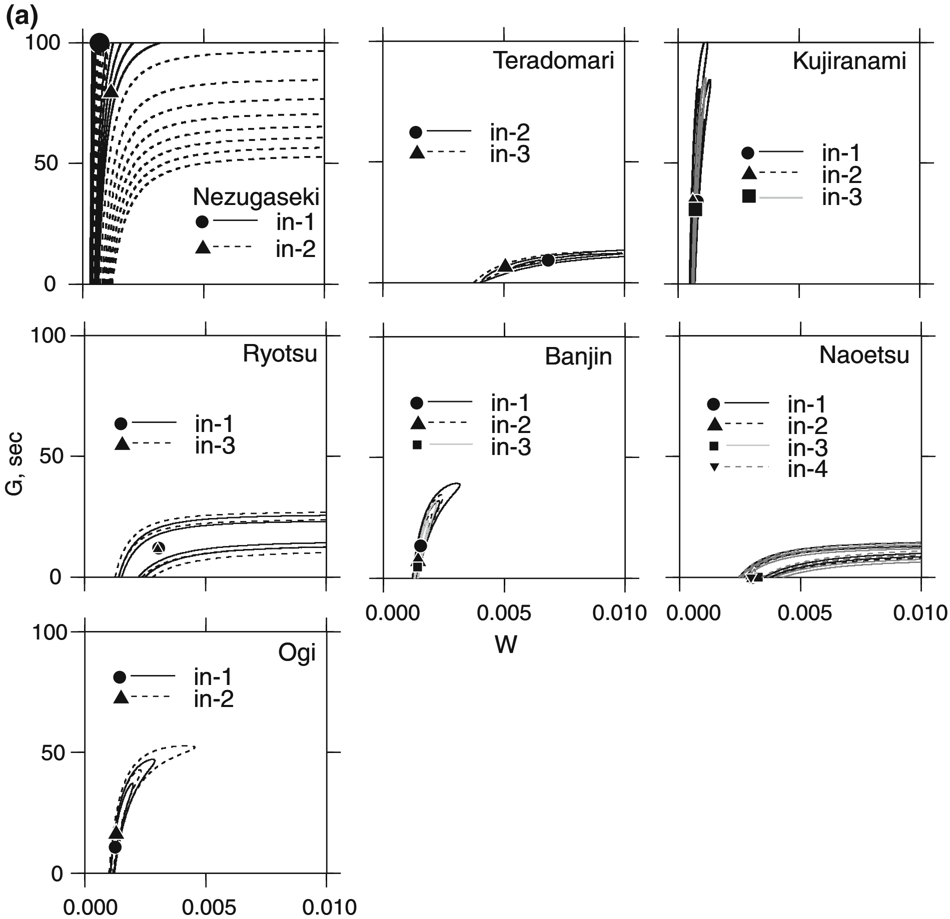

Figure 6
(a) Contour plot of the temporally averaged squared residual (TASR) of observed and calculated recovering well levels for inflow. The range of the contour lines is from 2×10^{-4} to 2×10^{-3} m^2 with intervals of 2×10^{-4} m^2 for Nezugaseki, while the range is from 1×10^{-5} to 2×10^{-5} m^2 with intervals of 1×10^{-5} m^2 for the other stations. The different lines (solid and dashed) and symbols indicate the different experiments. At Awashima, Iwafune, and Himekawa, the contour lines of TASR are not estimated because the responses of these tide gauges insignificantly influence recorded tsunami waveforms. (b) Same as (a), but for outflow. At Nezugaseki, only one outflow experiment was carried out, and therefore, the comparison is not made.

3.3. Nonlinear Response

The tide gauge response is modeled by a combination of linear and nonlinear response at Nezugaseki, Ryotsu, Ogi, Teradomari, Banjin, and Kujiranami, because the estimated best coefficients of G are not zero (Table 1). The nonlinear coefficients W are also estimated by the grid search method, assuming that the linear coefficients G are zero, correspond to a pure nonlinear response as adopted by the previous study (e.g., SATAKE

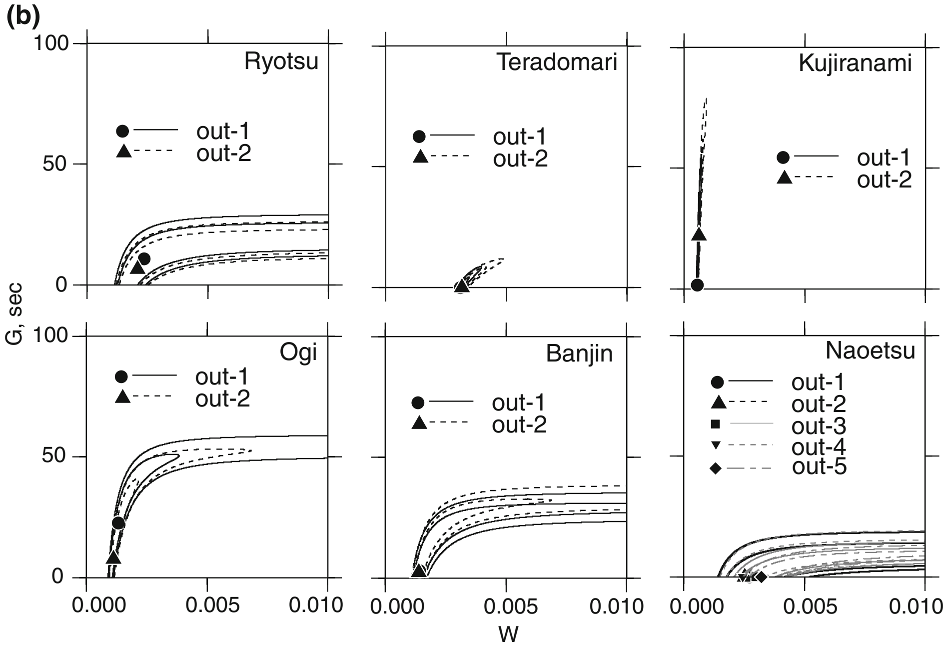

Figure 6
contd.

et al., 1988). We denote this nonlinear coefficient *Ww,* and the corresponding TASRw are also shown in Tables 1 and 2. In fact, TASRw is larger than or equal to the TASR. The effect of *W* and *Ww* on the waveform correction will be discussed in Section 4.3.

4. *Correction of Tsunami Waveforms of the Niigataken Chuetsu-oki Earthquake in 2007*

4.1. *Correction of the Tsunami Waveforms using the Best Linear and Nonlinear Coefficients*

In the previous section, we found that the correction for tide gauge response is necessary at Nezugaseki, Ryotsu, Ogi, Teradomari, Banjin, Kujiranami, and Naoetsu, but not at Awashima, Iwafune, and Himekawa. In this section, the tsunami waveforms of the Niigataken Chuetsu-oki Earthquake in 2007 at the former seven tide gauge stations are corrected using equation (4) and the best linear and nonlinear coefficients.

The original tide gauge records are digitally recorded at a sampling interval of 30 sec at Nezugaseki, Ogi and Kujiranami, and 6 sec at Teradomari. We resampled them at 60 sec interval for the correction. At Ryotsu, Banjin, and Naoetsu, the tsunami waveforms were recorded in analogue form. Hence we manually digitized the tsunami waveforms recorded on the paper sheets. We also resampled the digitized records at 60 sec intervals. Generally, manual digitization inevitably includes reading errors which mainly consist of high frequency components. In order to minimize these errors, a moving average filter, consisting of a Hanning window with 4 min full width, was applied to the digitized records. Because it makes the peaks of the records blunt, the peak values are replaced by the original ones, so that the original peak values are retained. The astronomical tide is removed by fitting polynomial functions.

The above tsunami waveforms at a sampling interval of 60 sec are corrected by using equation (4) with the best linear and nonlinear coefficients (Fig. 7). Note that in equation (4), we use the best coefficients of inflow for the upward motion, and those of outflow for the downward motion. At Banjin, where the largest amplitudes were originally recorded,

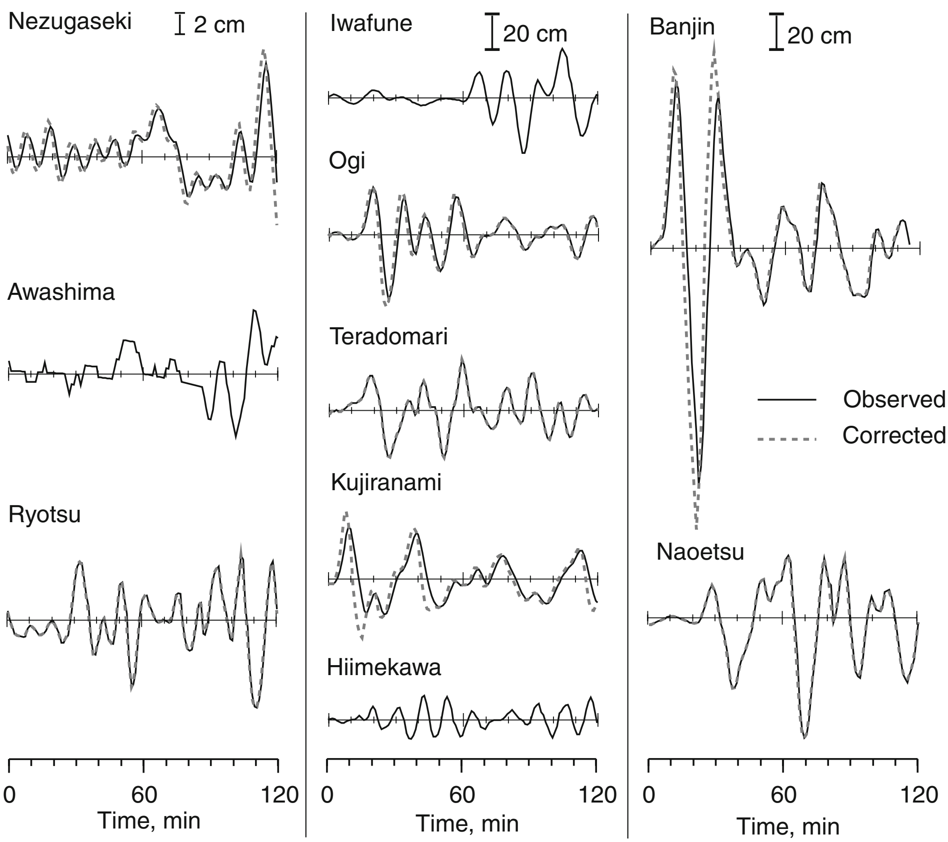

Figure 7

Corrected (gray dashed lines) and observed (black solid lines) tsunami waveforms of the Niigataken Chuetsu-oki Earthquake in 2007. Note the different amplitude scales for the left column. The tsunami waveforms at Nezugaseki, Ryotsu, Ogi, Teradomari, Kujiranami, Banjin, and Naoetsu are corrected. At the other tide gauge stations, only the original tsunami waveforms are shown because these tide gauge responses had no significant influence on the recorded tsunami waveform.

the first upward, downward, and second upward amplitudes after the correction become +103 cm, −163 cm, and +114 cm, respectively, while those of the original record are +96 cm, −137 cm, and +88 cm. It is noteworthy that the corrected waveform shows that the second upward amplitude becomes larger than the first one. The appearance of the above peaks shifts to at most a few minutes earlier than the peaks of the uncorrected records. Moreover, around Banjin tide gauge station, it was reported that the tsunami climbed up a quay, and the ground was slightly inundated. The inundation height was visually observed as 110 cm above the sea level at the time of tsunami arrival (Fig. 8). This height is in good agreement with the corrected maximum amplitude of +114 cm, indicating that the correction is reliable.

At Kujiranami, the corrected first upward and downward amplitudes become +41 cm and −31 cm, while those of the original records are +33 cm and −17 cm, respectively. The appearance of the above peaks also shifts to a few minutes earlier than the uncorrected

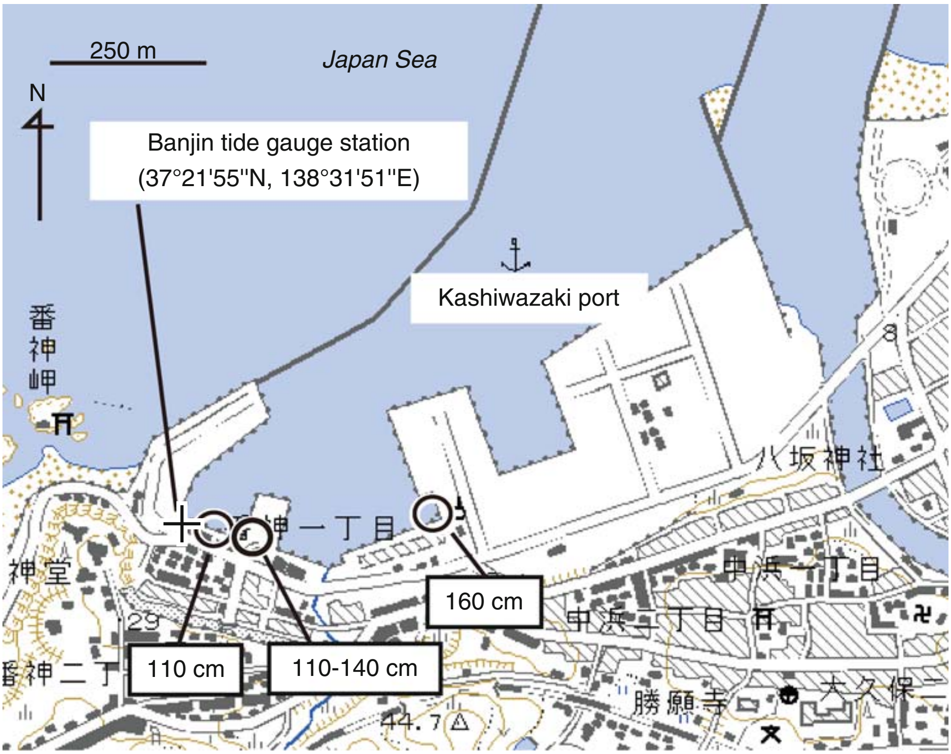

Figure 8
Map around the Banjin tide gauge station. The numerals indicate the tsunami inundation height of the Niigataken Chuetsu-oki Earthquake in 2007 above the sea level at the time of tsunami arrival. Around here, subsidence of a few cm was reported by GSI (Nishimura *et al.*, 2008), but the amount can be neglected in comparison with the tsunami inundation height. A topographical map with 1:25,000 scale provided by GSI is used.

peaks. At Ogi, the original waveform is similarly corrected. However, at Ryotsu, Teradomari, and Naoetsu, the corrected waveforms are similar to the original ones, despite values of G and W for these stations that would suggest a significant influence of both nonlinear and linear response components. This unexpected result is attributed to the relatively small amplitudes and long periods of the tsunami. At Nezugaseki, as mentioned in Section 3.1, the intake pipe was cleaned after the tsunami but before our *in situ* measurement. Therefore, the linear and nonlinear coefficients obtained by the *in situ* measurement may not represent the tide gauge response at the time of the tsunami, but we correct it tentatively using the coefficient only for the inflow (see Section 3.1).

4.2. *Effects of Variance of Linear and Nonlinear Coefficients on the Correction*

For the correction of tsunami waveforms, we used the best linear and nonlinear coefficients estimated from the repeated experiments as mentioned in Section 3.2. How do the corrected waveforms change if we use other pairs of coefficients? In order to examine the effect, we correct the tsunami waveforms by using all the pairs of the coefficients estimated by each experiment. For example, at Kujiranami, we carried out three inflow experiments and two outflow experiments. Hence three pairs for inflow and two pairs for outflow were estimated. Therefore, six corrected tsunami waveforms can be obtained, because the pairs for inflow and outflow are needed to correct the upward and downward waveforms, respectively. Comparison of these waveforms shows that there is a discernable difference in the corrected waveforms only at Kujiranami. The largest difference is obtained by the combinations of the linear and nonlinear coefficients of the third inflow and the second outflow experiments, and the second inflow and the second outflow experiments (Fig. 9), nonetheless the difference is insignificant. This indicates that variance in measurement of the coefficients does not influence the correction of tsunami waveforms significantly.

4.3. *Effect of Linear Response*

The results in Section 3.1 show that the linear response is needed for the correction of the tsunami waveforms at Nezugaseki, Ryotsu, Ogi, Teradomari, Banjin, and Kujiranami. What is the contribution of the linear response to the tsunami waveform correction? In order to examine the effect, we correct the tsunami waveforms by using the coefficients Ww in Tables 1 and 2, which are the nonlinear coefficients estimated by the grid search method by assuming the linear coefficient G is zero. At Nezugaseki the correction using Ww does not change the waveform, while the appearance of the corrected peaks with the combined linear and nonlinear coefficients becomes a few minutes earlier (Fig. 10a). This indicates that the effect of the linear response is larger than the nonlinear response, although it is still insignificant for correcting the tsunami waveforms. At Kujiranami, the negative amplitude corrected by using the nonlinear coefficient Ww is slightly larger than that by combined linear and nonlinear coefficients G and W (arrow in Fig. 10b).

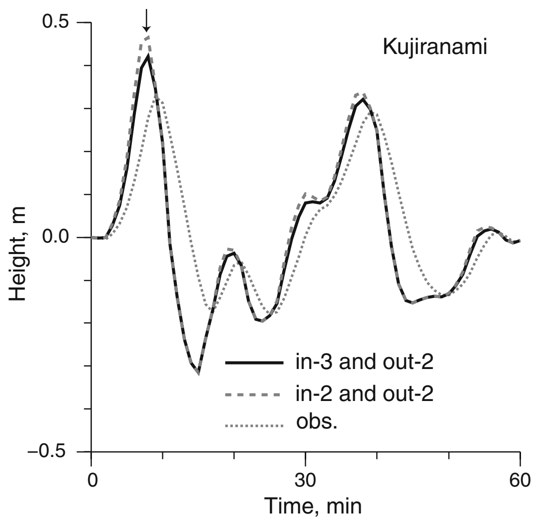

Figure 9
Comparison of the observed tsunami waveform with the corrected ones at Kujiranami. The correction using both linear and nonlinear coefficients for the third inflow and the second outflow experiments is shown by a solid line, while for the second inflow and outflow experiments shown by a gray dashed line. The original record is shown by a dotted line. The amplitudes of the first peak (arrow) are slightly different.

However, the difference is small compared with the difference between corrected and original tsunami waveforms. At the other tide gauge stations, no differences were recognized. That is to say, for the tsunami of the Niigataken Chuetsu-oki Earthquake in

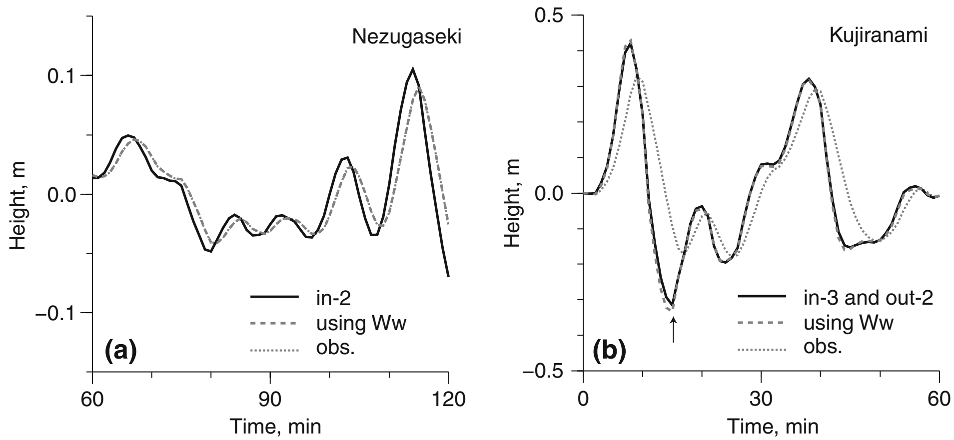

Figure 10
(a) Comparison of the corrected tsunami waveforms using the nonlinear-only coefficients *Ww* (gray dashed line) with those using the combined coefficients *G* and *W* (black solid line) at Nezugaseki. The original waveform (dotted line) is also shown. (b) Same as (a) but at Kujiranami. The difference was only at the negative peak (arrow).

2007, the effect of the linear response can be neglected. However, this does not necessarily mean that the linear response can always be neglected for other cases.

5. Conclusion

We carried out *in situ* measurements for the linear and nonlinear tide gauge responses at ten tide gauge stations, Nezugaseki, Awashima, Iwafune, Ryotsu, Ogi, Teradomari, Banjin, Kujiranami, Naoetsu, and Himekawa, on the Japan Sea coast of central Japan, and corrected the tsunami waveforms of the Niigataken Chuetsu-oki Earthquake in 2007. The results are summarized as follows.

(1) At Nezugaseki, Ryotsu, Ogi, Teradomari, Banjin, and Kujiranami, both linear and nonlinear components of the tide gauge response must be considered for the intermediate periods of a few to a few tens of minutes characteristic of tsunami energy. At Naoetsu, only the nonlinear component of the tide gauge response influences the tsunami waveform. At Awashima, Iwafune, and Himekawa, the response of the tide system negligibly effects the tsunami waveform, so that the correction was unnecessary.

(2) We corrected the tsunami waveforms from the Niigataken Chuetsu-oki Earthquake in 2007 with the measured tide gauge responses at Nezugaseki, Ryotsu, Ogi, Teradomari, Banjin, Kujiranami, and Naoetsu. The corrected amplitudes become higher and the peaks appear a few minutes earlier than the original ones at Banjin, Kujiranami, and Ogi. At Banjin, the original first upward amplitude of +96 cm, the first downward one of −137 cm, and the second upward one of +88 cm become +103 cm, −163 cm, and +114 cm, respectively. The amplitude of +114 cm coincides with the tsunami inundation height by visual observation. At the other stations, the differences of original and corrected tsunami waveforms are insignificant.

(3) The corrected tsunami waveform by the nonlinear coefficients is slightly different from that by the combined linear and nonlinear ones at Kujiranami. However, the difference is considerably smaller than the amplitudes of the first and second tsunami waves on the original tide gauge records and/or on the corrected tsunami waveforms. At the other tide gauge stations, the difference is insignificant. Therefore, the effect of the linear response for the tsunami of the Niigataken Chuetsu-oki Earthquake in 2007 can be neglected.

The tide gauge stations whose response was estimated in this study are a well type and located on the coast of the Japan Sea where the sea condition is severe in winter, and the intake pipes therefore need to be narrow. Our study indicates that tide gauge response to tsunami must be considered for such stations, particularly when the recorded tsunami period is short and the amplitude is large. While tide gauges usually respond well to record tsunami for other cases, other types (pressure gauges and acoustic gauges) are less costly and free from the effects of intake pipes.

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